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Impact of meteorological drought on hydrological drought in Toruń (central Poland) in the period of 1971–2015

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Abstract

The paper presents impact of meteorological drought on hydrological drought on the Vistula River in Toruń in the period of 1971–2015. It uses index method for the assessment of hydrological drought threat degree as a result of multi-month lasting meteorological drought. Based on the values of the *SPI*-24 (24-month standardized precipitation index) it was determined that meteorological drought in Toruń appeared six times and the total time of the phenomenon was 33% of the studied interval. Periods of hydrological drought on the Vistula River in Toruń have been determined based on the values of the *SWI*-24 (24-month standardized water level index). It has been found out that hydrological drought appeared four times and its total time was 10% longer that the meteorological drought. Based on the values of both indices (*SPI*-24 and *SWI*-24) correlation coefficient for months, seasons and years, it was found that the relation between both kind of droughts is weak ($r < 0.5$). That result is also confirmed in the distribution of both kinds of drought. Only in 32 months (8% of the total time) the intensity of the two simultaneously occurring drought was at least moderate. The achieved results revealed that the hydrological drought was occurring periodically, independent on meteorological drought. Hydrological drought was also influenced by the external factors (hydropower plant in Włocławek, Major Groundwater Basin – *GZWP*) and climate factors appearing in the upper and middle part of the river basin.

Key words: *drought indices, hydrological drought, meteorological drought, the Vistula River*

INTRODUCTION

Drought is one of the most adverse natural phenomena, which causes significant economic and social losses. Significant decrease of precipitation or lack of it cause disruption of natural and agricultural ecosystems and trouble with appropriate water management for the purposes of the economy. Since the 1970s until present, in many regions of the world it is observed that the number of multi-month meteorological drought increases and they become more and more burdensome to the society and lead to significant material losses [BORDI *et al.* 2009; LORENZO-LACRUZ *et al.* 2013; VICENTE-SERRANO *et al.* 2014]. The issue is also noted, monitored and a matter of numerous scientific analyses in Poland [JOKIEL 2004; ŁABĘDZKI 2007; RADZKA 2015; SOMOROWSKA 2009]. At the end of the twentieth century, on the significant part of Mid-Poland Lowlands, there have been recorded frequent cases of drought in spring months (April–June) with the phenomena maximum occurring in May. In the summer, the drought zone was extending to the other geographic regions of Poland and the number of dry months increased. Studies revealed that in the period of 1991–2000, in many regions of Poland, the number of hydrological droughts has increased as compared to the reference period of 1961–1990 [BĄK, MASZEWSKI 2012; SOMOROWSKA 2009; SOMOROWSKA, PIĘTKA 2012].

In the region of Kuiavia, which encompasses the area of Bydgoszcz–Toruń district, droughts cause significant economic and social problem. It is a lowland area with relatively poor hydrographic network. It is the region, in which the Poland's lowest annual precipitation is recorded [BARTCZAK *et al.* 2014; ŁABĘDZKI 2007]. Meteorological droughts are also the cause of numerous hydrological droughts of surface waters [GORĄCZKO *et al.* 2013; KUBIAK-WÓJCICKA 2012].

Further decrease of summer precipitation and periods of significant air temperature rise are being forecasted until mid-twenty first century in the above mentioned region [BĄK, ŁABĘDZKI 2014a, b; CZERNECKI, MIĘTUS 2015]. The result of precipitation decrease by approximately 17% relative to the last 30 years of the twentieth century will be appearance of at least a few multi-month meteorological droughts during summer (July–September), which may bring about hydrological droughts of various length and intensity.

Among the plurality of drought definitions found in the literature, one of the practical ways of drought parameters' determination is the index method, which uses standardization function known to the statistics. In case of the precipitation, commonly applied and recommended by the International Commission on Irrigation and Drainage (ICID) and the World Meteorological Organization (WMO) for the purposes of operational monitoring of drought threat is the *SPI* (standardized precipitation index) [MCKEE *et al.* 1993; 1995; WMO 2012]. The *SPI* is frequently quoted in Polish and international literature, especially in questions related to drought [BARKER *et al.* 2016; BĄK, ŁABĘDZKI 2002; BORDI *et al.* 2009; ŁABĘDZKI, BĄK 2014; NAM *et al.* 2015; PAOLO, PEREIRA 2006; STAGGE *et al.* 2015; TOKARCZYK, SZALIŃSKA 2014; ŠEBENIK *et al.* 2017; VIDO *et al.* 2015; XIE *et al.* 2013].

Meteorological drought of several months contributes to development of soil drought first, and then – agricultural drought. In case of hydrological and socio-economical drought, the response time is much longer. Depending on the type of research on the influence of meteorological drought on the other kinds of drought, the values of standardized indices, including the *SPI*, may be calculated in various time scales, from one to several or even several dozens of months. In case of short time periods, the dynamics of the analyzed index is high, while in the longer time periods, the course of the index values gets visibly softer [ŁABĘDZKI 2007; MCKEE *et al.*1993; 1995]. Various time scales assumed for the purposes of analyses sometimes leads to significant inconsistencies in the achieved results. It can be seen, among others, on the *SPI* distribution maps, which present the areas threatened by droughts or precipitation excess. Examples of such threat maps for the area of Poland, prepared by the Institute of Technology and Life Sciences (ITP), Poland, for the periods of 1, 12 and 24 months have been presented in Figure 1.

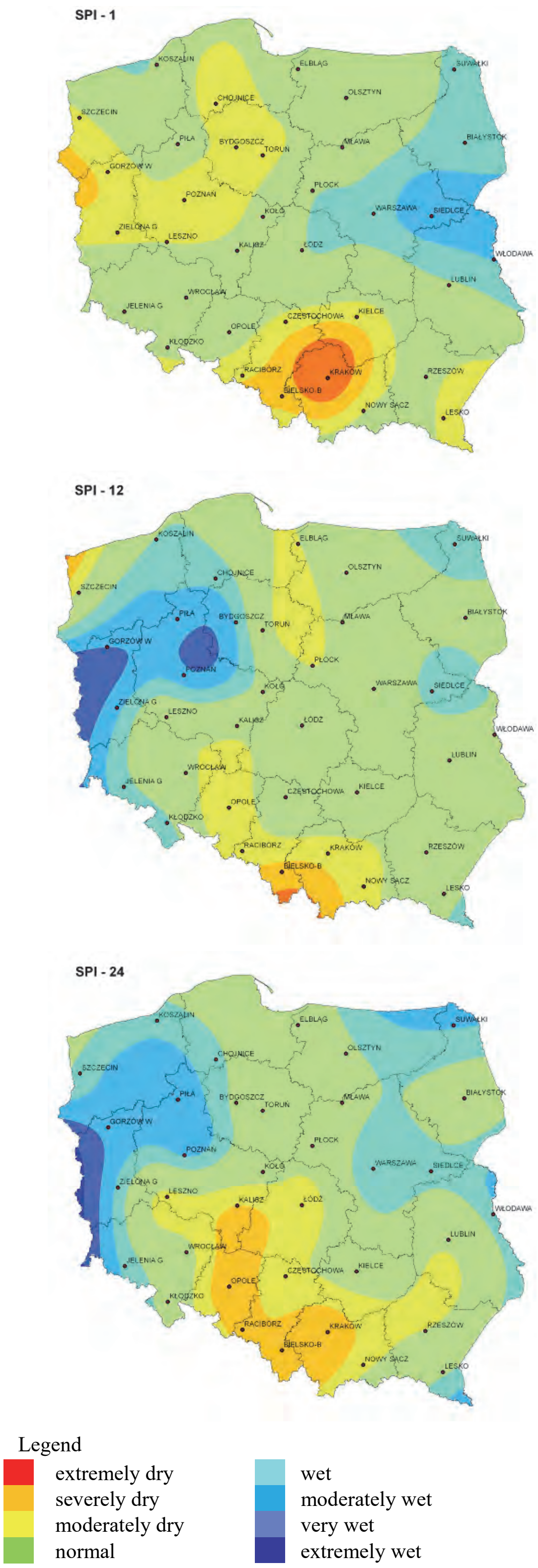

Fig. 1. The distribution of dry and wet areas in Poland (April, 2013) according to indices: standardized precipitation *SPI*-1, *SPI*-12 and *SPI*-24 (for multiply time scales 1-, 12- and 24-months); source: Institute of Technology and Life Sciences, Poland [2013]

As mentioned previously, the contribution to development of hydrological drought is long lasting (most often, several dozen of months) period of small or temporal lack of precipitation. Similarly to the meteorological drought, the hydrological drought can also be characterized with the use of standardized hydrological indices. In the literature, there exist, among others, the following two indices: *SWI* (standardized water level index) [BHUIYAN 2004; SAHOO *et al.* 2015] and *SRI* (standardized runoff index) [LORENZO-LACRUZ *et al.* 2013; SHUKLA, WOOD 2008]. The former one is calculated based on cumulated water levels, the latter one is based on the data related to cumulated discharge. The index method allows for determination of the relations between both kinds of drought. The relations strength in particular months, seasons and years may be assessed on the basis of the coefficient of correlation between values of the analyzed indices [ROSSI 2003; SIVAKUMAR, WILHITE 2002; TOKARCZYK, SZALIŃSKA 2014]. For the purposes of the indices calculation, there are used at least 30-year long measurement sequences, which take into account precipitation and hydrological conditions with various appearance probability.

The catchment's reaction to the precipitation shortage is diverse and primarily depends on physiographic catchment features (soil permeability, topography, land use and land cover), climatic conditions (mainly precipitation and evaporation) and water management [GÓMEZ GÓMEZ, PÉREZ BLANCO 2012; TOKARCZYK, SZALIŃSKA 2014; VAN LOON, LAAHA 2015; WEN *et al.* 2011]. According to LORENZO-LACRUZ *et al.* [2013] the most severe hydrological droughts do not always occur in areas with the intense meteorological droughts, because their severity is also influenced by other factors, like amount of water consumed by the industry and society, effectiveness of water management and meteorological conditions in river's upper course. The influence of climatic factors (precipitation, high air temperature, high evaporation) and diverse external conditions may mitigate or aggravate hydrological drought as well as delay it in the relation to the beginning of meteorological drought. VAN LOON and LAAHA [2015] claim that as much as 30 various factors may influence water level and discharge in the main water current. TOKARCZUK and SZALIŃSKA [2014] compared the influence of meteorological drought on hydrological drought in highland and lowland regions of Poland and came to the conclusion that it is different. Mountain rivers are characterized by high dynamics of precipitation and hydrological conditions, in both excess and deficiency of precipitation. The rate of changes on the lowland areas is much lower and the hydrological drought intensity in more dependent on external factors.

In the light of numerous evidence showing climate change in Poland and increased number of drought periods, the aim of the paper was the assessment of relationship between long lasting meteorological drought and hydrological drought on Vistula River in Toruń in the period of 1971–2015. The study has taken into consideration the influence of local non-climate factors and climatic factors appearing in the Vistula Basin. The achieved knowledge will allow to assess the hydrological drought threat on Vistula in Toruń and the study results may be used for local planning of water management strategies in cases of a crisis [BARKER *et al.* 2016; LINNEROOTH-BAYER *et al.* 2015].

METHODS

STUDY AREA

The study concerns meteorological and hydrological droughts in Toruń in the period 1971–2015. The Toruń region and the adjacent area of Eastern Greater Poland (wschodnia Wielkopolska) are ones of the driest regions in Poland. The water gauge in Toruń is located on 734.7 km of the Vistula River course, its zero point level above the sea level is 31.981 m. The gauge closes the river's basin area of 181,033 km^2, which comprises 93.11% of the whole Vistula's basin area [GLAZIK, KUBIAK-WÓJCICKA 2009]. The largest Vistula's tributaries are Narew with Bug, Wkra, Skrwa and Bzura.

The most important external local factors include the influence of hydropower plant located at the Włocławek Reservoir and uniform recharge of the Vistula River coming from underground water in the Toruń area. On the other hand, small consumption by the industry and society in the area of Toruń does not have a significant influence on hydrological parameters of Vistula in that region [GIERSZEWSKI *et al.* 2013; GRZEŚ 1991; KLECZKOWSKI 1990; KUBIAK-WÓJCICKA 2014b; POMIANOWSKA 1999]. It is noteworthy that the Vistula in Toruń is a transit river and its resources are formed mainly in upper and middle part of the basin. Recharging of the Vistula River with water coming from those regions often lead to mitigation of hydrological drought intensity, despite the occurrence of meteorological drought.

CLIMATE AND HYDROLOGICAL DATA

Meteorological data (precipitation) and hydrological data (water levels) have been collected in the period between February 1969 and December 2015. In both cases the data comes from The Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB). Monthly precipitation *P* (mm) have been calculated based on the daily measurements from weather station in Toruń and the monthly average water levels *WL* (cm) – based on daily observations of the Vistula River water levels in gauging station in Toruń.

APPLIED DROUGHT INDICES

Based on the index method, there have been determined the periods of meteorological drought in Toruń and the periods of hydrological drought on the Vistula River in Toruń, there have been calculated the parameters of both kinds of drought (beginning and end of drought, duration of the phenomenon, magnitude and intensity of the phenomenon) and assessed the relationship between both kinds of drought in particular months, seasons and years with use of the values of the correlation coefficient.

For the purpose of determination of meteorological drought, there have been used monthly precipitation sums recorded in the weather station in Toruń in the period of 1971–2015. In purpose of determination of hydrological drought, there has been used the *SWI* index, which was calculated based on average monthly water levels of the Vistula River in Toruń in the period of 1971–2015.

The values of *SPI* and *SWI* indices are the standard deviation of precipitation and water levels from the median value in the multi-year period. In the study, matching to the normal distribution of homogenous series of precipitation *P*-24 has been achieved with use of the transformation function $f(P) = \sqrt[3]{x}$ [BĄK, ŁABĘDZKI 2002]. In case of water levels *WL*-24, for the purposes of normalization function, a 2-parameter logarithmic function has been used [OZGA-ZIELIŃSKA, BRZEZIŃSKI 1994; VICENTE-SERRANO *et al.* 2012]. Positive result of the compatibility test of the distribution of the transformed variable with the normal distribution allows for calculation of the indices' values based on the following equation:

$$X = \frac{f(X) - \mu}{\delta} \tag{1}$$

where: X = chosen index (*SPI*, *SWI*); $f(X)$ = transformed sums of precipitation (water levels); μ = mean of normalized index X, δ = standard deviation of index X.

Following MCKEE *et al.* [1993; 1995], it has been assumed that in the period of drought all the values of the *SPI* and *SWI* indices are negative and at the same time, at least in one month those values are less or equal –1.0. Drought is interrupted when value of an index rises above zero. Determined drought periods may be characterized with the following parameters: duration expressed in number of months (*D*) drought magnitude (*DM*) and intensity (*I*). Drought magnitude is described as absolute sum of index values during the drought. Drought intensity is the quotient of drought magnitude (*DM*) and its duration (*D*). Maximal intensity of drought period translates to minimal value of the index recorded during the phenomenon. For both indices, which values satisfy the condition $X < -1.0$, there has been assumed a common, 4-class intensity assessment (Tab. 1), which has been modeled on the classification proposed by [MCKEE *et al.* 1993; 1995].

Table 1. Classification of drought intensity

SPI, SWI	Intensity of drought
< –2.0	extremely dry
(–1.99; –1.5]	severely dry
(–1.49; –1.0]	moderately dry
(–0.99; 0.0]	mild dry

Source: own elaboration based on MCKEE *et al.* [1993].

As hydrological drought is formed as a result of extended period of small precipitation, the analysis of 24-month sums of precipitation *P* and average water levels *WL* was conducted. For a such long time scale, the indices are less sensitive to temporal changes, as suggested in former studies [ŁABĘDZKI 2007]. As hydrological drought is formed as a result of extended period of small precipitation, there has been assumed the suggested by the literature analysis of 24-month sums of precipitation *P* and average water levels *WL*, which are less sensitive to momentary changes [ŁABĘDZKI 2007]. In practice, it meant that at the end of each month in the analyzed period, the sums of both parameters were cumulated for 24 months, i.e. for the current month and 23 preceding months. The above methodology was used to prepare input data for calculation of the indices of both kinds of drought in the period of 1971–2015 marked as *SPI*-24 and *SWI*-24.

The relations between droughts have been assessed on the basis of the coefficients of correlation between indices *SPI*-24 and *SWI*-24 in the periods of month, in summer season (April–September) and in winter season (October–March) and in calendar year. The division to summer and winter periods has significant meaning due to the length of navigation season, which in Poland lasts from April to October. Drought occurrence in summer has particular meaning to inland navigation, both passenger and cargo because of lack of sufficient transit depth [KUBIAK-WÓJCICKA 2014a].

RESULTS

PRECIPITATION AND WATER LEVELS

It has been concluded that in the period of 1971–2015, the average multi-year precipitation sum *P*-24 in Toruń was 1088 mm and was changing in the range from 1083 mm to 1093 mm. The smallest 24-month precipitation sum *P*-24 has been recorded in January 1984 – 743 mm and the highest one – in October 1981 – 1541 mm. In particular months, the values of precipitation variability coefficient was changing in the range 14-16%. At the same period, the average multi-year sum of cumulated annual water levels *WL*-24 was 7580 cm, with the changes belonging to the range from 7580 cm to 7604 cm. Monthly minimum of 5766 cm was recorded in December 2015 and the maximum – in May 1982 – 9967 cm. In particular months, the variability coefficient of that hydrological parameter was almost constant at approximately 12% (Tab. 2).

Table 2. Statistics of 24-monthly sums of precipitation *P*-24 (mm) and 24-average monthly sums of water level *WL*-24 (cm) in Toruń in the years 1971–2015

Statistics	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Precipitation *P*-24, mm												
Mean	1092	1092	1093	1091	1088	1087	1087	1085	1086	1085	1083	1084
SD	163	164	162	159	155	154	165	156	160	167	168	164
Maximum	1537	1530	1530	1519	1529	1459	1523	1502	1464	1541	1540	1523
Minimum	743	752	758	747	764	800	792	792	800	764	746	741
Median	1095	1077	1087	1072	1094	1087	1053	1081	1086	1076	1068	1091
RSD	15%	15%	15%	15%	14%	14%	15%	14%	15%	15%	16%	15%
Water level *WL*-24, cm												
Mean	7604	7603	7602	7590	7586	7582	7576	7571	7567	7564	7559	7552
SD	898	918	928	923	922	913	905	901	902	899	898	907
Maximum	9682	9751	9953	9953	9967	9863	9692	9371	9212	9298	9429	9485
Minimum	6198	6189	6162	6233	6298	6221	6170	6085	5989	5903	5828	5766
Median	7634	7688	7625	7605	7549	7540	7593	7568	7608	7595	7653	7525
RSD	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%	12%

Explanations: *SD* = standard deviation, *RSD* = relative standard deviation.
Source: own study.

THE METEOROLOGICAL AND HYDROLOGICAL DROUGHTS

The course of changes of *SPI*-24 and *SWI*-24 in the analyzed period has been presented in Figure 2.

The values of the index *SPI*-24 was changing from 2.6 in May 1982 to –2.4 in January and April 1984. At the same time they were strongly bound to precipitation sums *P*-24 (statistically significant value of correlation coefficient r^2 = 0.98, α = 0.05). Similar extreme values were recorded for the index *SWI*-24: maximum in the period March–May 1982 (2.3) and minimum in December 2015 (–2.2). In this case, there was also recorded a significant, strong dependence between cumulated sums of water levels *WL*-24 and the values of the index *SWI*-24 (r^2 = 0.99; α = 0.05). Periods of meteorological and hydrological droughts have been determined on the basis of *SPI*-24 and *SWI*-24 value distribution in the analyzed period in accordance with the assumed methodology and the selected statistics, which characterize both kinds of drought presented in Table 3.

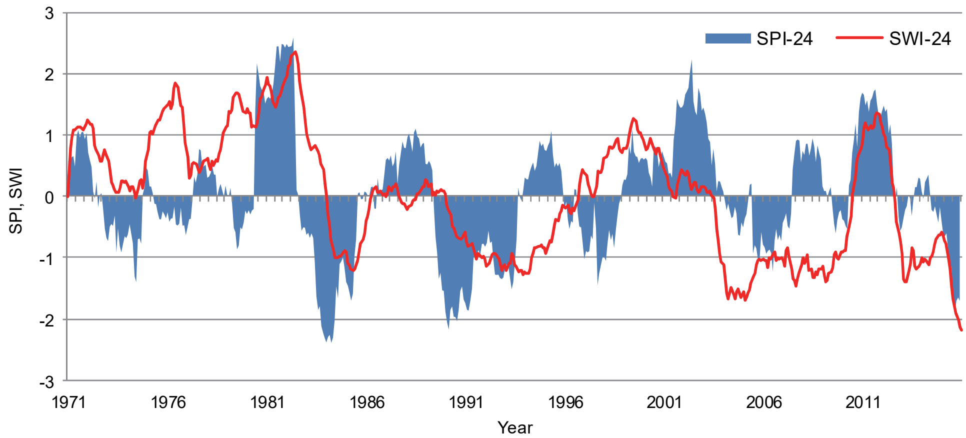

Fig. 2. Course of standardized precipitation index for 24-month time scale (*SPI*-24) and standardized water level index for 24-month time scale (*SWI*-24) in the years 1971–2015; source: own study

Table 3. Statistics of meteorological and hydrological droughts in Toruń (1971–2015)

Drought parameters	Standardized precipitation index for 24-month time scale (*SPI*-24)		Standardized water level index for 24-month time scale (*SWI*-24)	
	value	period	value	period
Event numbers	6	–	4	–
The longest duration, months	51	VI 1989–VIII 1993	83	I 1990–VIII 1996
Average duration of drought, months	30	–	9.0	–
Maximum magnitude of drought	67.3	VI 1989–VIII 1993	96.6	VII 2003–V 2010
Minimum value of index	–2.4	I 1984 IV 1984	–2.0	XII 2015
Average intensity of drought	–1.0	–	–1.0	–

Source: own study.

In the analyzed multi-year period, there have been found 6 meteorological and 4 hydrological droughts. The longest meteorological drought lasted 51 months and the shortest one – 18 months (Tab. 4). Meteorological drought appeared in 176 months, which comprises approximately 33% of the analyzed period. In case of the hydrological drought the values were respectively as follows: maximum – 83 months, minimum – 26 months, total – 230 months (43%). Simultaneous occurrence of both kinds of drought has been found in 104 months (25% of total number of months) but in 32 months (8%) only the intensity of both kinds

Table 4. Distribution of meteorological (*SPI*-24) and hydrological (*SWI*-24) droughts in Toruń in the years 1971–2015

Year	Month												Year	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	standardized precipitation index for 24-month time scale (*SPI*-24)													standardized water level index for 24-month time scale (*SWI*-24)											
1971													1971												
1972										-0.2	-0.5	-0.7	1972												
1973	-0.7	-0.5	-0.5	-0.5	-0.3	-0.9	-0.5	-0.8	-0.9	-0.8	-0.7	-0.7	1973												
1974	-0.6	-0.5	-0.6	-0.8	-1.3	-1.4	-0.7	-0.7	-0.8				1974												
1975													1975												
1976													1976												
1977													1977												
1978													1978												
1979													1979												
1980													1980												
1981													1981												
1982									-0.3	-0.6	-0.5	-0.5	1982												
1983	-0.6	-0.6	-0.7	-0.6	-0.7	-1.1	-1.6	-1.9	-1.8	-2.1	-2.2	-2.3	1983												
1984	-2.4	-2.3	-2.3	-2.4	-2.3	-2.0	-1.5	-1.7	-1.1	-1.1	-1.0	-1.2	1984	-0.3	-0.4	-0.7	-0.9	-1.0	-1.0	-1.0	-1.0	-1.0	-0.9	-0.9	-0.9
1985	-1.4	-1.5	-1.6	-1.7	-1.6	-1.0	-0.7						1985	-1.1	-1.1	-1.2	-1.2	-1.2	-1.1	-1.1	-0.9	-0.8	-0.7	-0.6	-0.4
1986													1986	-0.3	-0.2										
1987													1987												
1988													1988												
1989						-0.2	-0.7	-0.9	-1.4	-1.3	-1.5	-1.6	1989												
1990	-1.9	-2.1	-2.2	-1.9	-1.8	-2.0	-2.0	-2.0	-1.9	-1.6	-1.5	-1.7	1990	-0.1	-0.2	-0.3	-0.5	-0.5	-0.6	-0.7	-0.7	-0.7	-0.7	-0.6	-0.6
1991	-1.7	-1.9	-1.9	-1.7	-1.5	-1.0	-1.0	-0.9	-0.9	-1.0	-0.8	-0.8	1991	-0.8	-0.8	-0.8	-0.8	-0.9	-0.9	-1.0	-0.9	-1.0	-1.0	-1.0	-1.0
1992	-0.8	-0.8	-0.6	-0.8	-0.7	-1.0	-1.3	-1.3	-1.3	-1.3	-1.4	-1.3	1992	-1.1	-1.1	-1.0	-1.0	-0.9	-0.9	-1.0	-1.0	-1.1	-1.2	-1.1	-1.1
1993	-1.2	-1.1	-1.1	-1.3	-1.5	-1.4	-1.1	-0.7					1993	-1.2	-1.1	-1.1	-0.9	-1.0	-1.1	-1.1	-1.2	-1.2	-1.2	-1.3	-1.2
1994													1994	-1.3	-1.3	-1.2	-1.0	-0.9	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8
1995													1995	-0.9	-0.8	-0.7	-0.7	-0.6	-0.5	-0.4	-0.4	-0.3	-0.2	-0.1	-0.2
1996									-0.3	-0.5	-0.5	-0.8	1996	-0.2	-0.1	-0.3	-0.3	-0.2	-0.2	-0.2	-0.1				
1997	-1.0	-0.9	-0.9	-0.9	-0.6	-0.7	-0.1	-0.5	-1.5	-1.3	-1.1	-1.0	1997												
1998	-1.0	-1.1	-0.8	-0.6	-0.7	-0.6	-0.9	-0.6	-0.3	-0.1	-0.1		1998												
1999													1999												
2000													2000												
2001													2001												
2002													2002												
2003													2003							-0.2	-0.5	-0.7	-0.9	-1.1	-1.1
2004													2004	-1.4	-1.6	-1.7	-1.6	-1.5	-1.6	-1.7	-1.6	-1.5	-1.6	-1.7	-1.6
2005								-0.8	-0.9	-1.0	-1.0	-0.6	2005	-1.7	-1.7	-1.6	-1.5	-1.4	-1.3	-1.3	-1.1	-1.0	-1.0	-1.0	-1.0
2006	-0.8	-0.8	-0.9	-0.9	-0.9	-0.9	-1.2	-0.7	-0.5	-0.7	-0.6	-0.7	2006	-1.1	-1.1	-1.2	-1.0	-1.0	-0.9	-0.9	-1.1	-1.0	-1.0	-1.0	-1.0
2007	-0.4	-0.4	-0.3	-0.5	-0.5	-0.3							2007	-1.1	-0.9	-0.9	-1.0	-1.2	-1.3	-1.4	-1.5	-1.4	-1.3	-1.1	-1.0
2008													2008	-1.1	-1.1	-1.0	-1.2	-1.2	-1.3	-1.3	-1.2	-1.3	-1.2	-1.2	-1.1
2009													2009	-1.3	-1.4	-1.4	-1.2	-1.2	-1.2	-1.0	-0.9	-1.0	-1.0	-0.9	-0.9
2010													2010	-0.9	-0.9	-0.7	-0.6	-0.3							
2011													2011												
2012													2012								-0.1	-0.4	-0.6	-0.7	-0.9
2013													2013	-1.3	-1.4	-1.4	-1.2	-1.1	-0.8	-0.9	-1.2	-1.2	-1.2	-1.1	-1.0
2014							-0.2	-0.3	-0.2	-0.3	-0.4	-0.2	2014	-1.1	-1.0	-1.1	-1.1	-1.0	-1.0	-0.9	-0.8	-0.7	-0.6	-0.6	-0.6
2015	-0.4	-0.6	-0.7	-0.6	-0.9	-1.3	-1.1	-1.7	-1.9	-1.7	-1.7	-1.7	2015	-0.6	-0.7	-0.8	-1.0	-1.2	-1.5	-1.7	-1.8	-1.9	-2.0	-2.1	-2.2

Legend: extremely dry; very dry; moderately dry; month with drought spell acc. to methodology of MCKEE *et al.* [1993; 1995]

Source: own study.

of drought was at least moderate. In two cases hydrological drought occurred as a result of meteorological drought (from January 1984 to February 1986 and from January 1990 to August 1996), in the remaining cases it was starting earlier (Tab. 4).

RELATIONSHIPS BETWEEN METEOROLOGICAL AND HYDROLOGICAL DROUGHTS

Relationships between drought kinds have been assessed on the basis of correlation coefficients between *SPI*-24 and *SWI*-24 (Tab. 5) in various time frames: a month, a season and a calendar year. In all the cases it has been found that the relationship between meteorological drought in Toruń and hydrological drought on the Vistula River is weak ($r < 0.5$). The strongest relationships have been found in spring months (Mar–Apr, $r = 0.47$) and the weakest – in the autumn-winter period (Sep–Oct, $r = 0.38$). In course of changes of the correlation coefficient within a calendar year there can be distinguished a period of increase in winter and spring and a period of decrease in summer.

Table 5. Correlation coefficients *r* between *SWI-24* and *SPI-24*

Parameter	Correlation in month, period														
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I–XII	IV–IX	X–III
r	0.44	0.46	0.47	0.47	0.44	0.44	0.39	0.39	0.38	0.38	0.41	0.45	0.43	0.41	0.45

Source: own study.

EXTERNAL FACTORS INFLUENCE ON THE COURSE OF HYDROLOGICAL DROUGHT

Based on the review of the available literature, the authors suggest that the reasons for weak relationships between the droughts should be sought in external factors, both in the area of Toruń and those appearing in the Vistula Basin, which contribute to temporal increase of water level and hence weaken or even suppress the hydrological drought. The most important local external factor, which significantly influences Vistula River's water level fluctuations in the region of Toruń is Włocławek Reservoir built in 1970. The reservoir was created as a result of damming the Vistula River in Włocławek, approximately 60 km above water gauge in Toruń. Its area is 70.4 km^2 and capacity is 370 million m^3. It is a typical lowland dam reservoir with quick water exchange. Average water retention time is only 5.2 days [GIERSZEWSKI *et al.* 2013]. The reservoir mitigates the Vistula River's floods below the dam at minimal degree but is restricts very low water levels. During initial period of existence of the reservoir, on the Vistula River below the dam in Włocławek, the discharge was changing a few times during a day in a range of 500–2000 $m^3 \cdot s^{-1}$ and the amplitude of water level fluctuations corresponding to those changes was approximately 1.5 m. All due to the peak working regime of the hydropower plant. The changes were taking place in intervals of 2 to 3 hours [STĘPIEŃ 1977]. Since 2002, the hydropower plant has been working in a flow through regime [BABIŃSKI, HABEL 2013]. An important external factor, which contributes to the water level increase in the Vistula River in Toruń is underground water recharge. In the area of Toruń, there is the Major Groundwater Basin [*GZWP*-141] located, in which large amount of fresh water has been collected [KLECZKOWSKI 1990; POMIANOWSKA 1999]. Water intake is relatively small and it does not influence significantly the drought intensity.

In some circumstances, despite the sustained meteorological drought, the hydrological drought was mitigated or suppressed due to main Vistula stream being recharged by the Carpathian and the middle course tributaries. According to KUBIAK-WÓJCICKA [2014b] in the period of 1951–2010, there were 270 days with water level exceeding the alarm level (650 cm) and an average frequency of the exceed was once every 2 years. The largest floods appeared in 1997, 1998, 2006 and 2010 [MACIEJEWSKI *et al.* 2011]. The phenomenon of meteorological drought with parallel exceeding alarm water levels in the river (lack of hydrological drought) occurrences took place in spring. A long and snowy winter was followed by major recharge of Vistula with thawing snow and ice. Cases of so called thaw floods were recorded in spring of 1976 and 1979 [GRZEŚ 1991].

CONCLUSIONS

In the light of the presented calculations and analyses supported by the literature review, it can be assumed that hydrological drought threat in Toruń is intermittent and not always is caused by a local meteorological drought. Based on mutual distribution of both kinds of drought and the revealed strength of relationships between them, it has been found weak and only periodically moderate influence of meteorological drought on hydrological drought in the analyzed period. The study of the influence of meteorological drought on hydrological drought proposed in the paper is only an initial phenomenon assessment. A comprehensive approach should also include the influence of external factors, which periodically strengthen or weaken the relationships.

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Wpływ suszy meteorologicznej na suszę hydrologiczną w Toruniu (centralna Polska) w latach 1971–2015

STRESZCZENIE

W artykule przedstawiono wpływ suszy meteorologicznej na suszę hydrologiczną na Wiśle w Toruniu w latach 1971–2015. W tym celu wykorzystano metodę wskaźnikową do oceny stopnia zagrożenia suszą hydrologiczną w wyniku wystąpienia wielomiesięcznej suszy meteorologicznej. Na podstawie wartości wskaźnika *SPI*-24 (ang. standardized precipitation index) dla 24-miesięcznego okresu stwierdzono, że susza meteorologiczna w Toruniu wystąpiła sześć razy, a łączny czas trwania zjawiska wynosił 33% badanego wielolecia. Okresy suszy hydrologicznej dla Wisły w Toruniu wyznaczono na podstawie wartości wskaźnika *SWI*-24 (ang. standardized water level index) dla 24-miesięcznego okresu. Stwierdzono, że susza hydrologiczna pojawiła się cztery razy, a jej łączny czas trwania był dłuższy o 10% od suszy meteorologicznej. Bazując na wartościach współczynnika korelacji między wartościami obu wskaźników (*SPI*-24 i *SWI*-24) w miesiącach, sezonach i latach stwierdzono słabą zależność między obiema suszami ($r < 0,5$). Wynik ten ma potwierdzenie także w rozkładzie obu susz. Tylko w 32 miesiącach (8% badanego wielolecia) intensywność obu jednocześnie występujących susz była co najmniej umiarkowana. Uzyskane wyniki świadczą, że susza hydrologiczna występowała okresowo niezależnie od suszy meteorologicznej. Na przebieg suszy hydrologicznej miały również wpływ lokalne czynniki zewnętrzne (elektrownia wodna we Włocławku, zbiornik wód podziemnych GZWP) oraz czynniki klimatyczne występujące w górnej i środkowej części dorzecza Wisły.

Słowa kluczowe: *susza hydrologiczna, susza meteorologiczna, Wisła, wskaźniki suszy*